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# Collective Flow and HBT Radii from a Full 3D Relativistic Hydrodynamic Model



平野哲文(東大理)

第4回原子核理論新人論文賞

受賞論文:

“Is early thermalization achieved only near midrapidity in Au+Au collisions at  $\sqrt{s_{NN}} = 130 \text{ GeV?}$ ”,  
T.Hirano, Phys. Rev. C 65, 011901 (2002).

*Many thanks to  
The QGP society,  
high energy physics group @Waseda  
and nuclear theory group @Tokyo*

# Recent Development of Our Hydrodynamic Model

1. A full 3D hydrodynamic model in  $\tau$ - $\eta_s$  coordinate
  - Non-central collisions
  - Rapidity dependence

} Simultaneously
2. Consideration of early chemical freeze-out
  - Particle ratio and spectra
  - A more realistic picture of hydrodynamic evolution
3. Incorporation jets into hydro (the Hydro+Jet model)
  - Dynamical effects of fluids on jet quenching

原子核理論  
新人論文賞

## Reference:

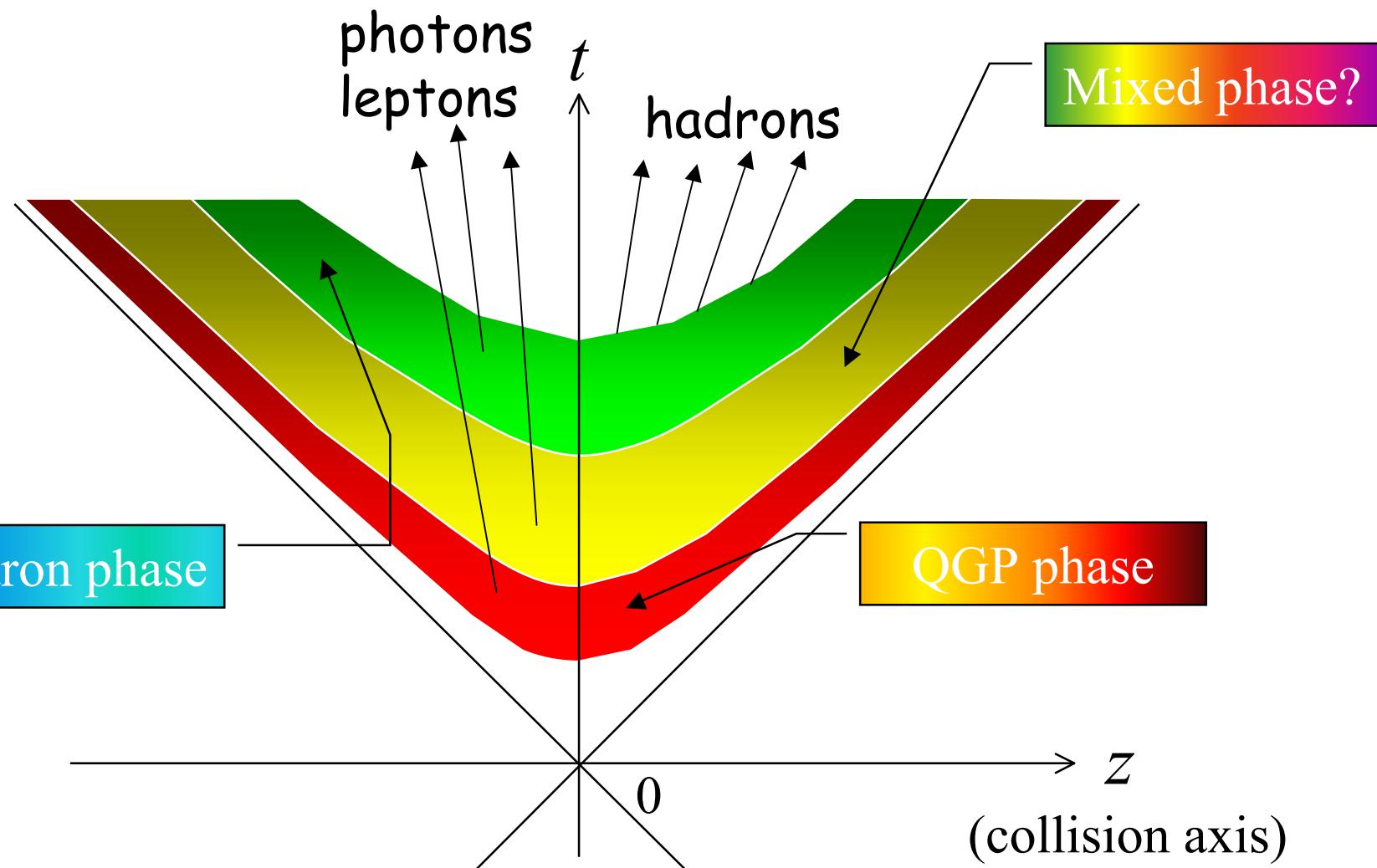
1. T.Hirano, PRC65,011901(2002).
2. T.Hirano and K.Tsuda, nucl-th/0205043.
3. T.Hirano and Y.Nara, hep-ph/0208029.



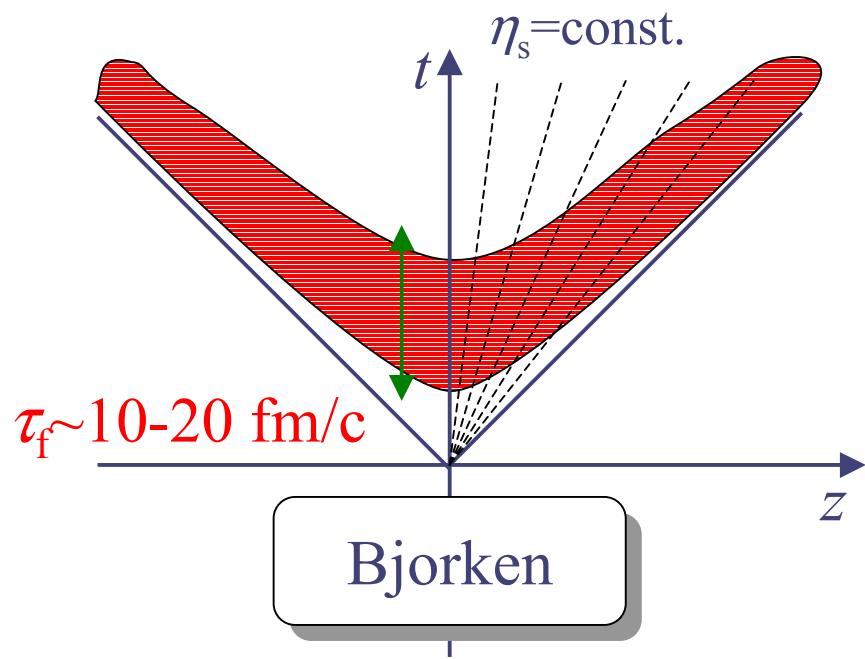
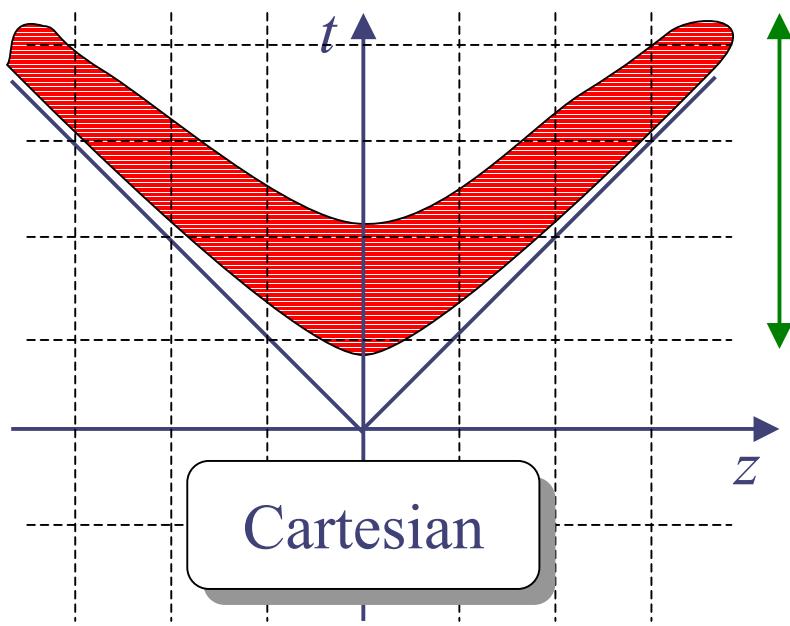
# **1. Full 3D Hydro**



# Schematic Picture of Space-Time Evolution



# Cartesian and ‘Bjorken’ Coordinates



## Problems:

- Too long life time  $t_f \sim 100 \text{ fm}/c$
- Less accurate near light cone
- Initial time  $\neq$  thermalization time

$$\left\{ \begin{array}{l} \tau = \sqrt{t^2 - z^2} \\ \eta_s = \frac{1}{2} \ln \frac{t+z}{t-z} \end{array} \right.$$

# Hydrodynamic Equation in $(\tau, \eta_s, x, y)$ -Coordinate

$$\partial_\tau \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{pmatrix} + \nabla \cdot \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{pmatrix} \tilde{\mathbf{v}} + \begin{pmatrix} \tau \partial_x P \\ \tau \partial_y P \\ \partial_{\eta_s} P \\ \tau \nabla \cdot P \tilde{\mathbf{v}} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ U_3 / \tau \\ U_4 \tilde{v}_{\eta_s}^2 / \tau + P(1 + \tilde{v}_{\eta_s}^2) \\ 0 \end{pmatrix} = 0$$

Here,

$$\begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{pmatrix} = \begin{pmatrix} \tau \tilde{\gamma}^2 (E + P) \tilde{v}_x \\ \tau \tilde{\gamma}^2 (E + P) \tilde{v}_y \\ \tau \tilde{\gamma}^2 (E + P) \tilde{v}_\eta \\ \tau \tilde{\gamma}^2 (E + P) - \tau P \\ \tau \tilde{\gamma} n_B \end{pmatrix}, \quad \begin{aligned} \tilde{v}_x &= \frac{\cosh Y_f}{\cosh(Y_f - \eta_s)} v_x \\ \tilde{v}_y &= \frac{\cosh Y_f}{\cosh(Y_f - \eta_s)} v_y \\ \tilde{v}_\eta &= \tanh(Y_f - \eta_s) \\ \tilde{\gamma} &= \frac{1}{\sqrt{1 - \tilde{\mathbf{v}}^2}} \end{aligned}$$

$Y_f \equiv \eta_s$  corresponds to Bjorken's scaling solution for longitudinal velocity.

# **2. Early Chemical Freeze Out**

# Early Chemical Freeze Out

$T^{\text{ch}} \neq T^{\text{th}}$

↑                      ↑

Particle ratio       $p_T$  spectra & HBT

Incorporate into hydrodynamics  
( $\mu_B=0$ )

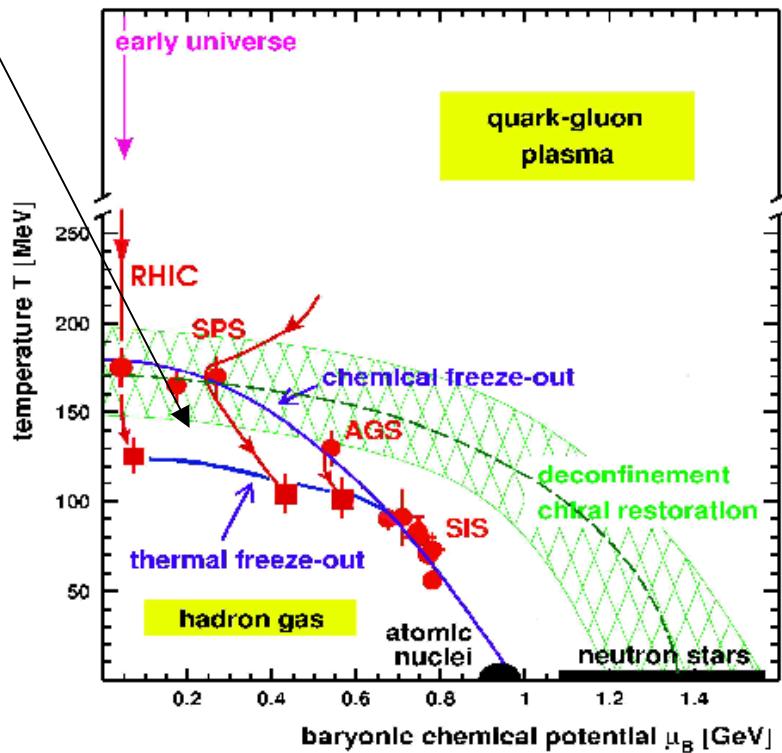
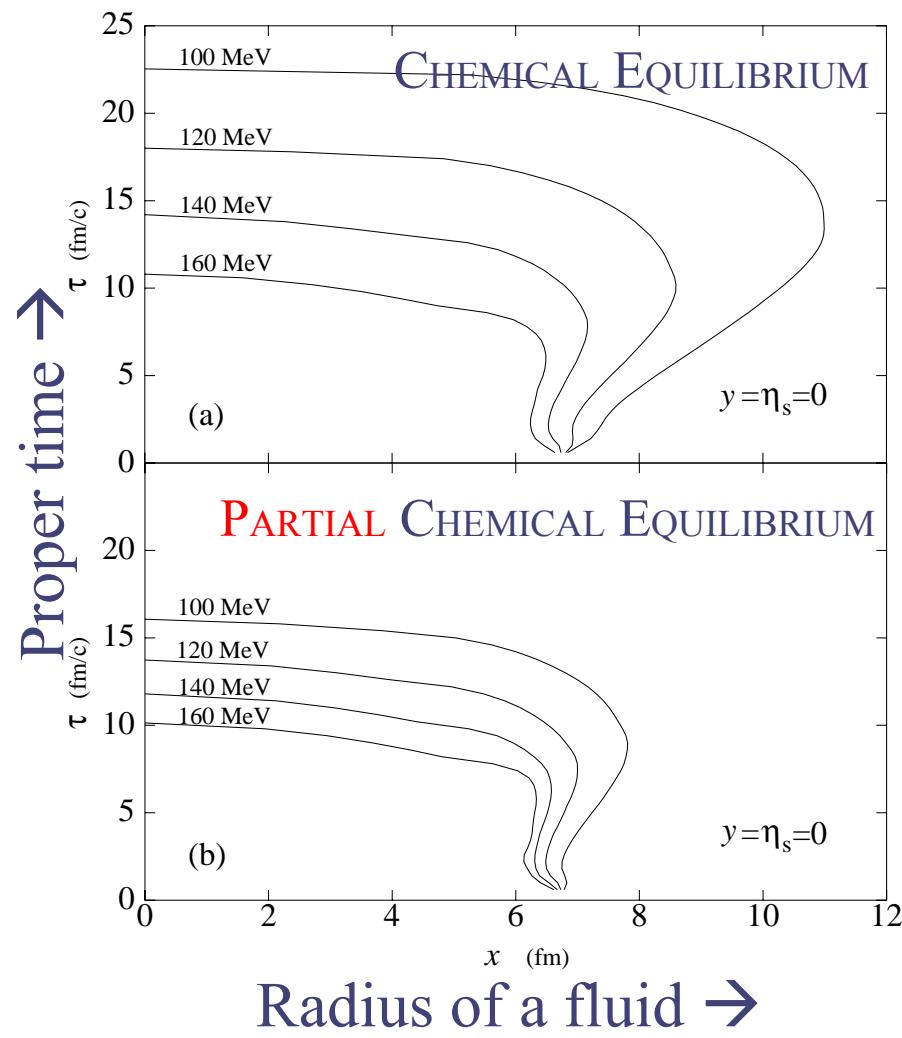
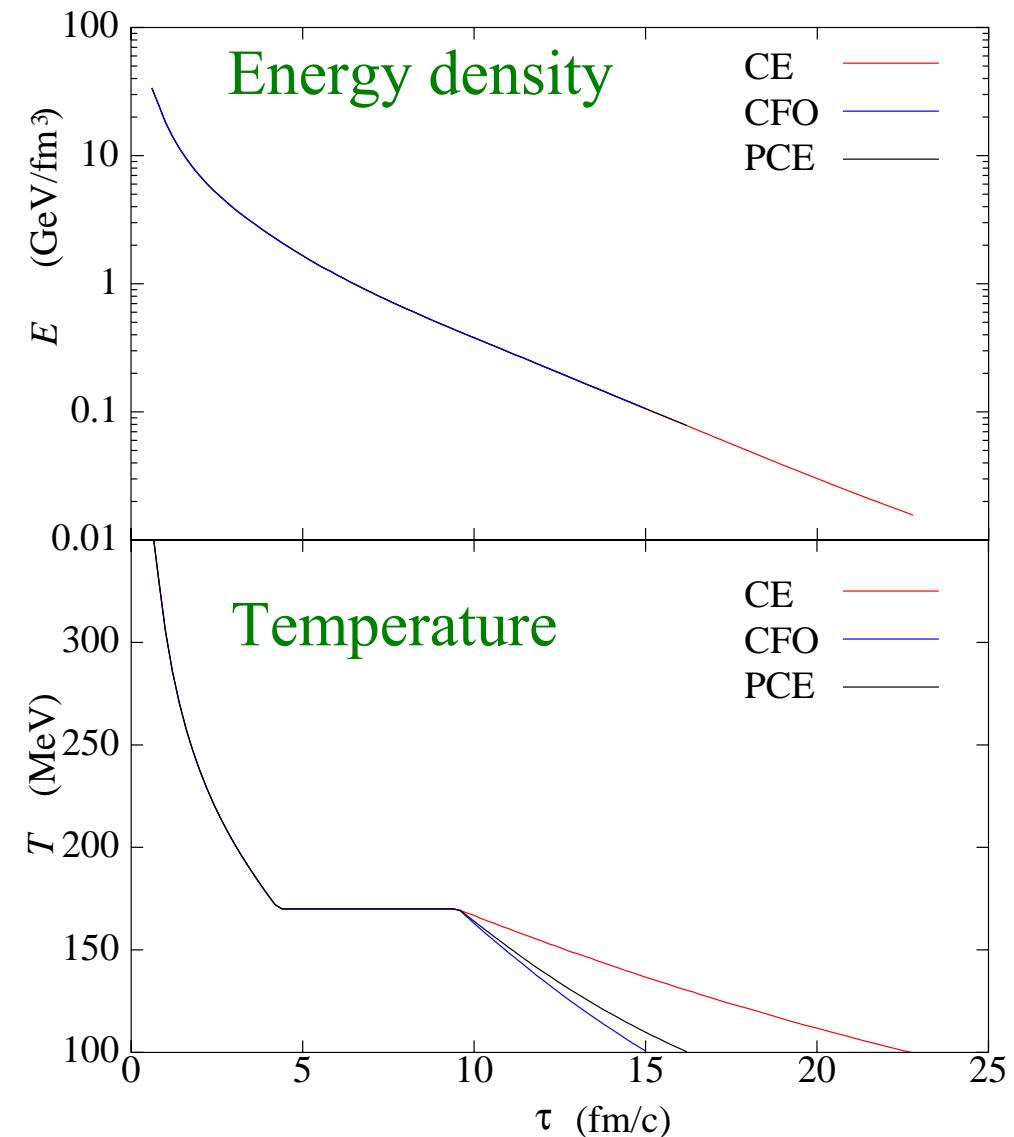


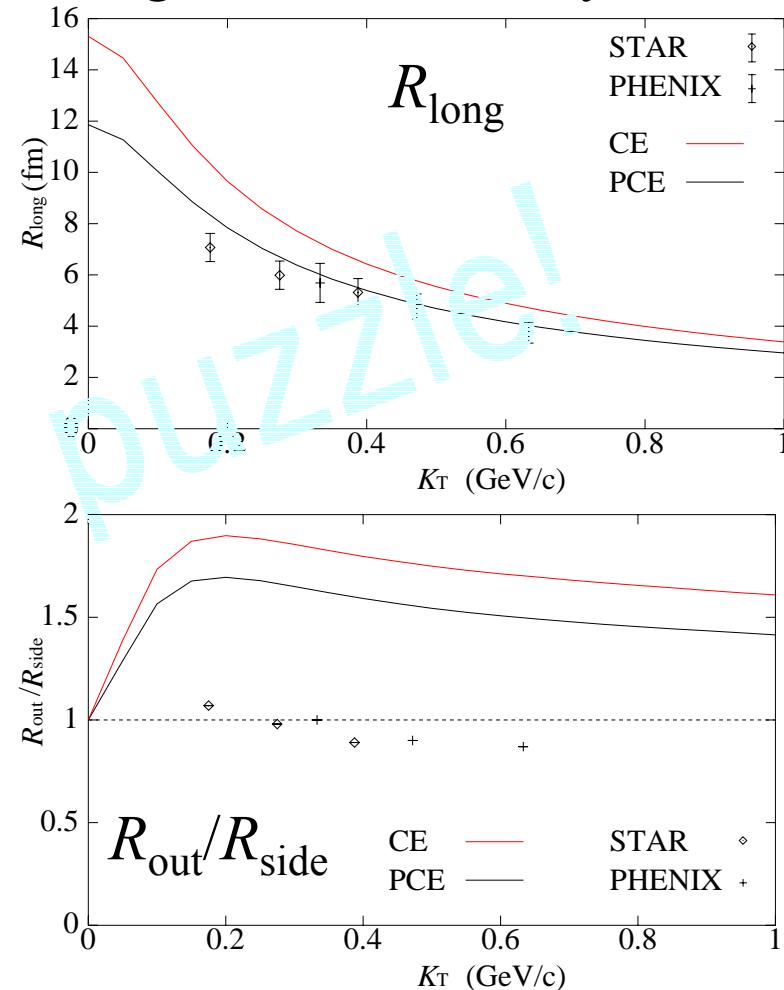
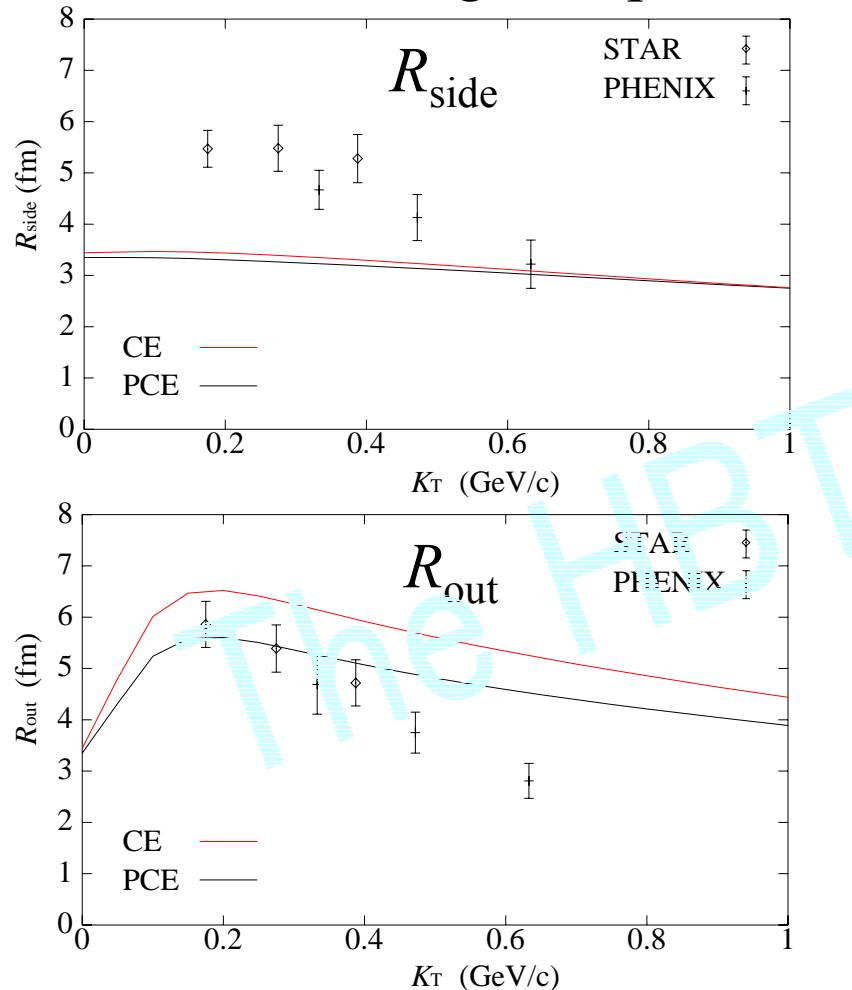
Figure from  
U.Heinz, hep-ph/0109006.

# Space-Time Evolution of Fluids



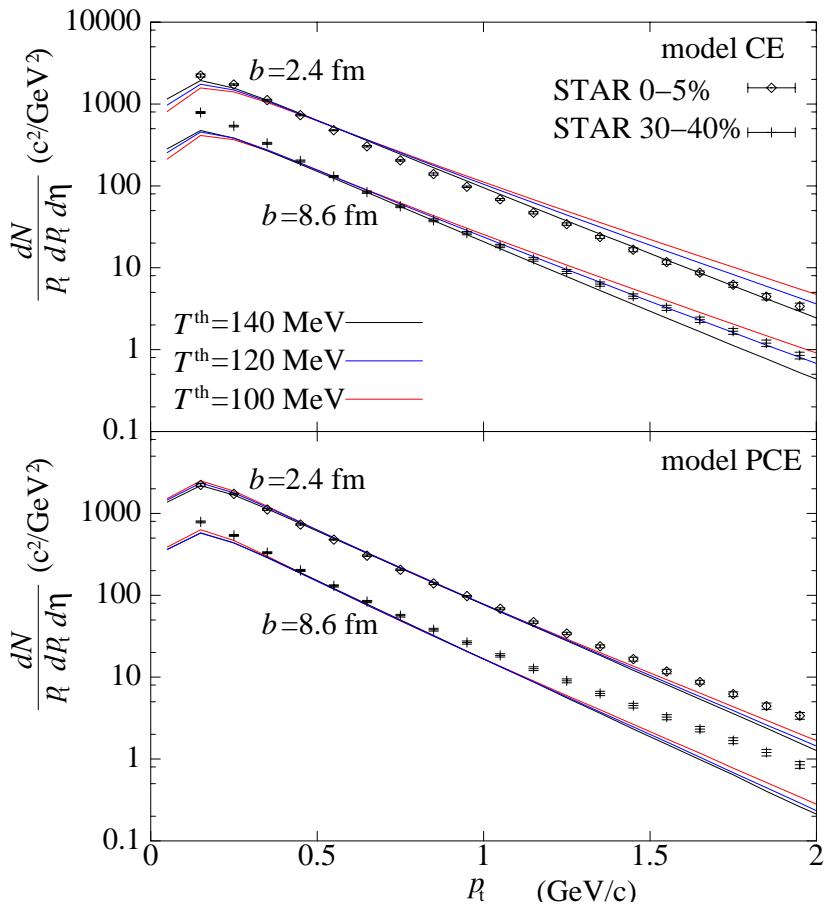
# $K_T$ Dependence of HBT Radii

- $T^{\text{th}}=140$  MeV, negative pions, neglecting resonance decays.

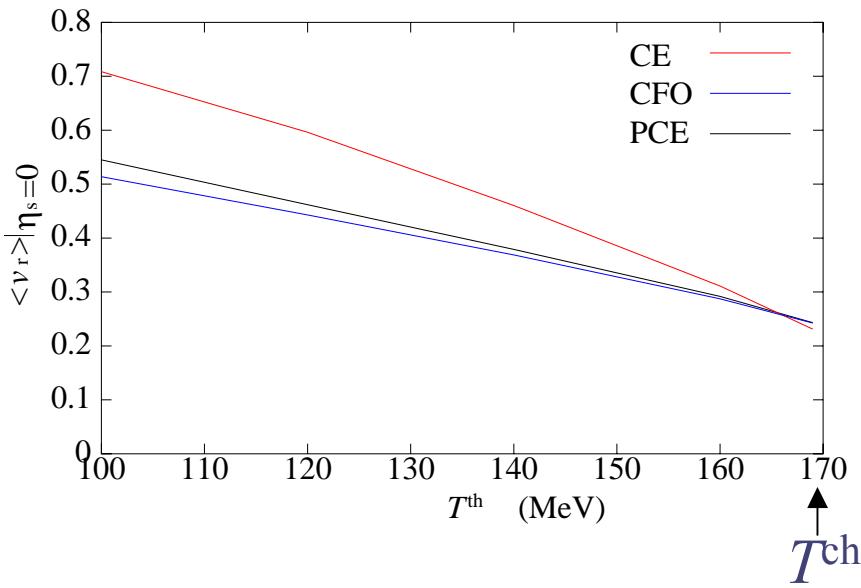


Data from STAR, PRL87, 082301 (2001), PHENIX, PRL88, 192302 (2002).

# $p_T$ Spectra of Charged Hadrons in Au+Au 130A GeV

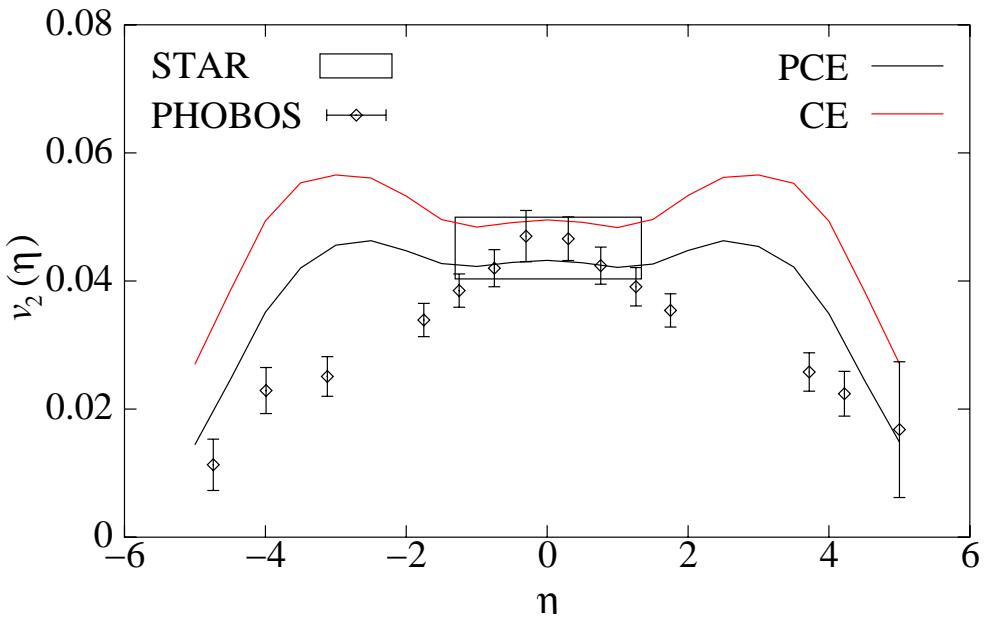


Data from STAR, PRL87,112303(2001);  
nucl-ex/0111004.



Almost constant  $p_T$  slope  
parameter  
→ Hard contribution  
above  $p_T \sim 2 \text{ GeV}/c$ ?

# Elliptic Flow as a Function of Pseudorapidity



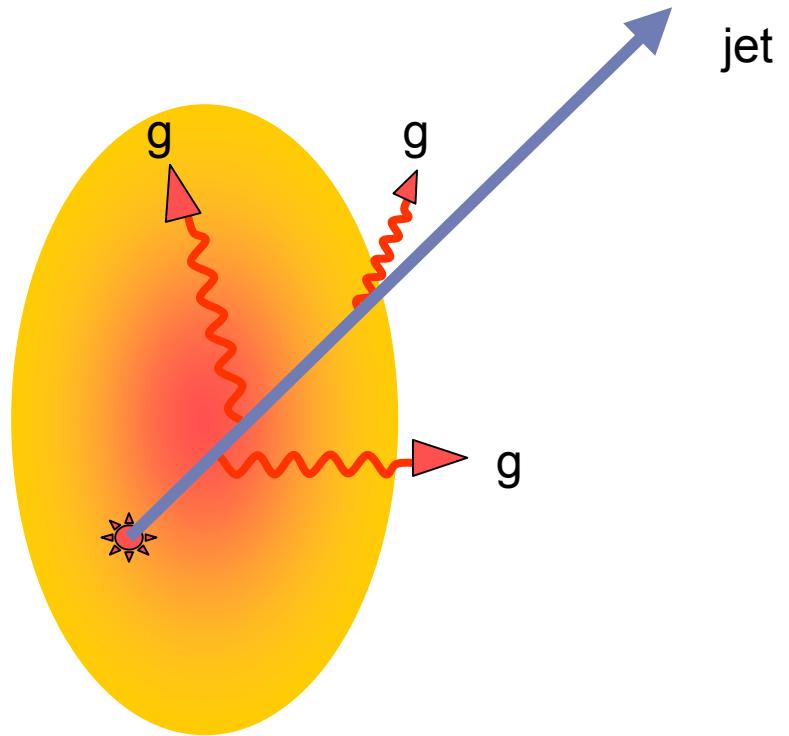
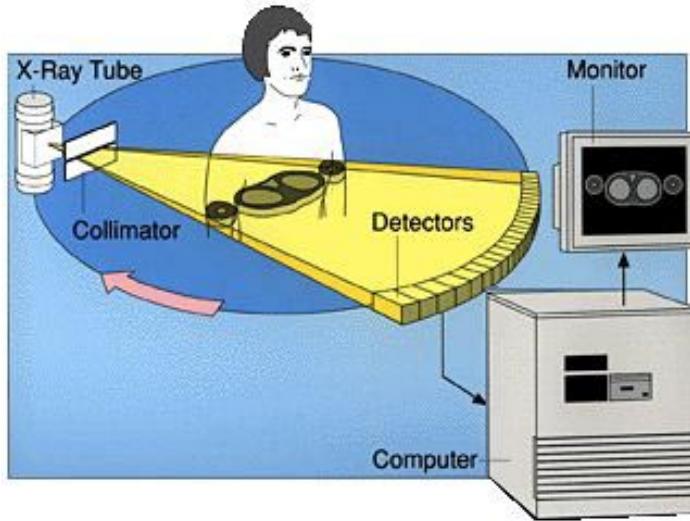
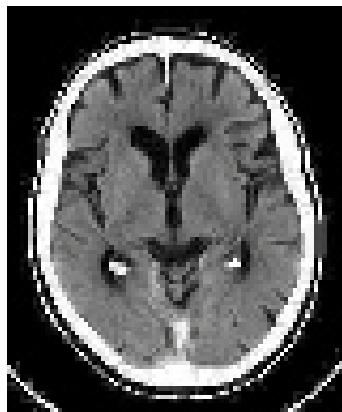
Our results ( $T^{\text{th}}=140$  MeV):  
 $0 < p_t < 2$  GeV/ $c$ , “min. bias”  
PHOBOS:  
All  $p_t$ , accepted data  
STAR:  
 $0.1 < p_t < 2$  GeV/ $c$ , min. bias

- First hydrodynamic result of  $v_2(\eta)$
- Elliptic flow is suppressed by early chemical freeze-out!
- Is early thermalization achieved only near midrapidity ?



# 3. Hydro+Jet

# Jet Tomography

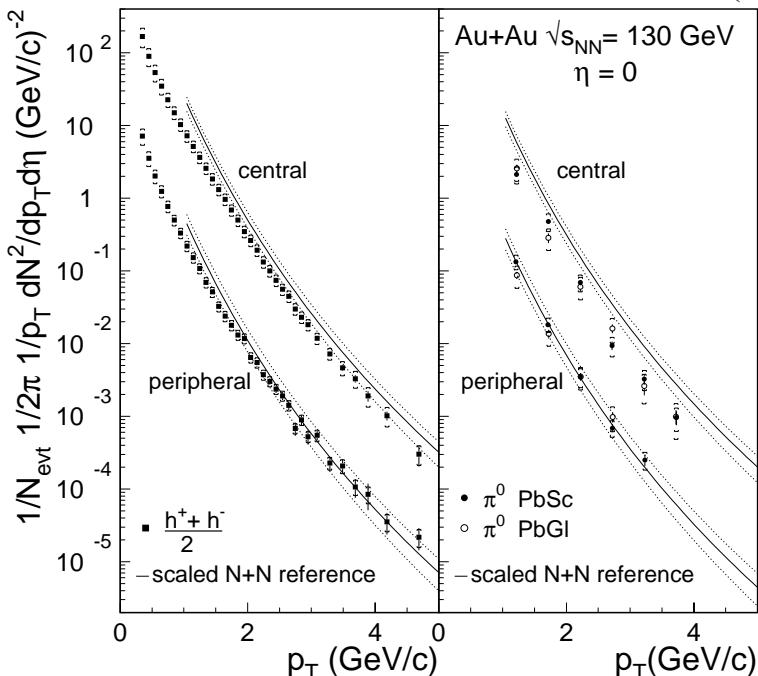


Does jet quenching contain information about QGP?

Figures from M.Gyulassy's talk

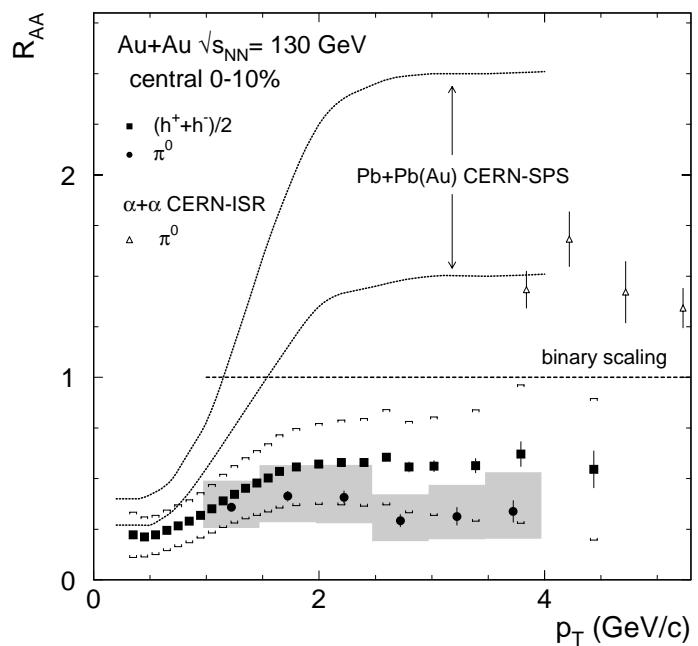
# Exp. Data @ High $p_{\text{T}}$

K.Adcox et al. (PHENIX), PRL88, 022301.



$$\langle b \rangle = 3.35 \text{ fm}$$

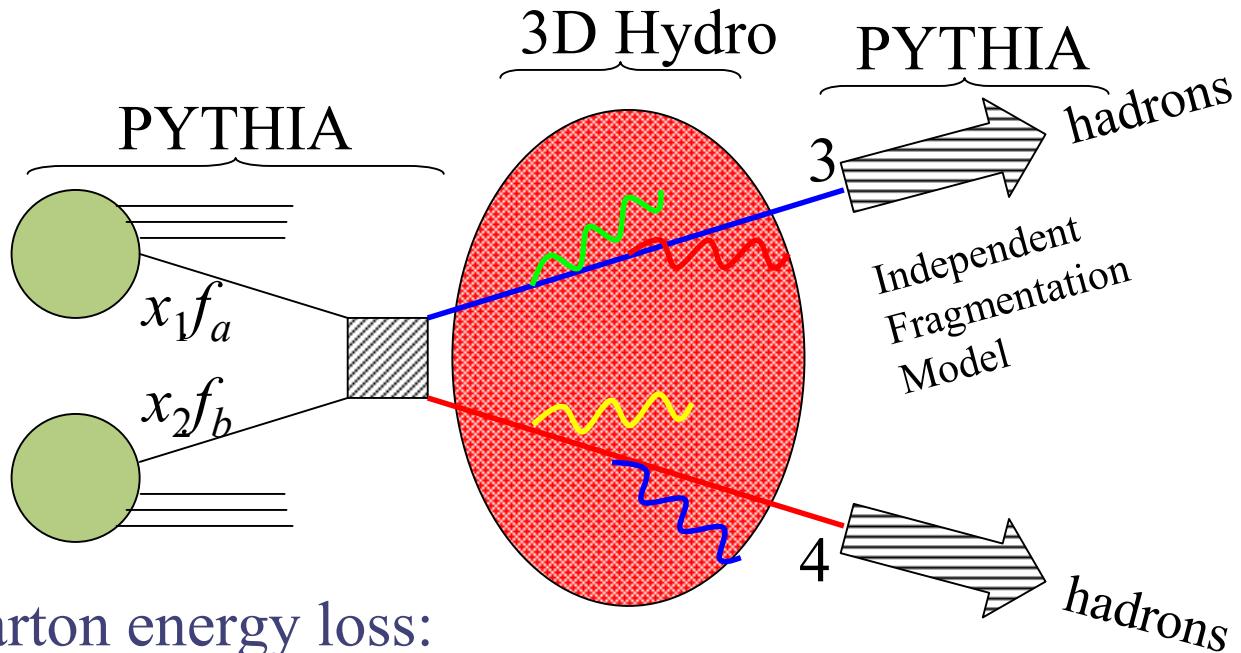
$$\langle b \rangle = 12.1 \text{ fm}$$



$$R_{\text{AA}}(p_{\text{T}}) = \frac{d^2 N^{A+A} / dp_{\text{T}} d\eta}{\langle N_{\text{binary}} \rangle d^2 N^{N+N} / dp_{\text{T}} d\eta}$$

First observation of jet quenching in H.I.C. !

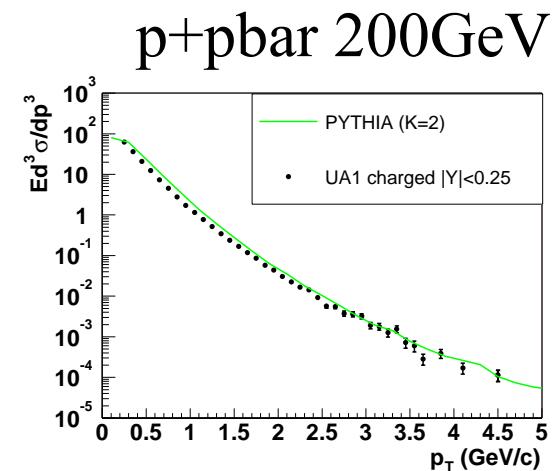
# Hydro+Jet Model



Parton energy loss:

$$\frac{dE}{dx} = \frac{\varepsilon}{\lambda} = \varepsilon \sigma \rho(\tau, r)$$

$\lambda$ : mean free path  
 $\rho$ : thermalized parton density  
 $\sigma$ : parton-parton cross section  
 $\varepsilon$ : energy loss per scattering

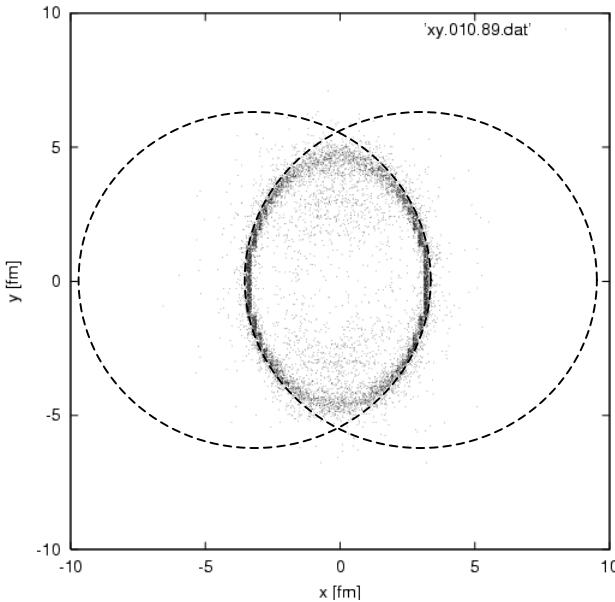
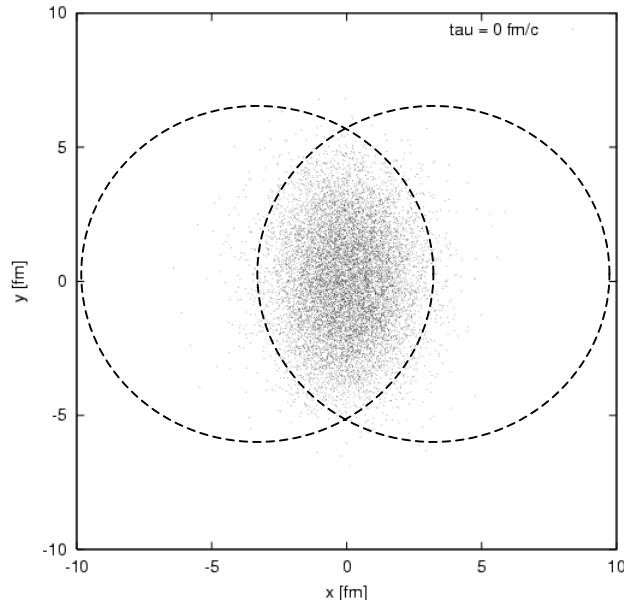


Parton density in the mixed phase

$$\rho = f_{\text{QGP}}(\tau, r) \rho(T_C)$$

$$f_{\text{QGP}} = \frac{E(\tau, r) - E_{\text{had}}}{E_{\text{QGP}} - E_{\text{had}}}$$

# Parton Evolution in the Transverse Plane

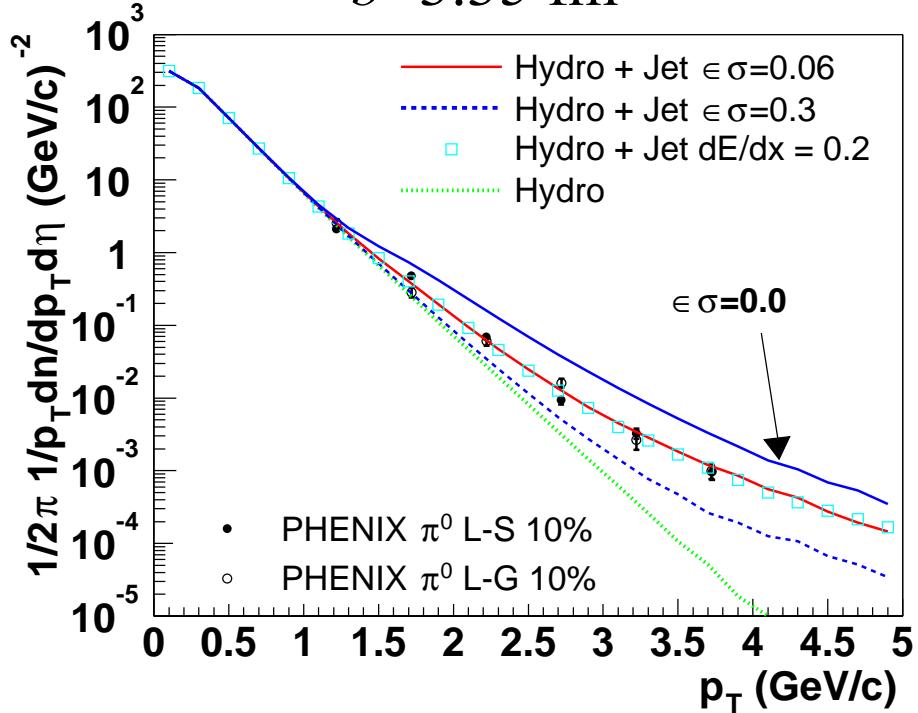


- Initial position of partons  
→ Prop. to # of **binary collisions**
- Momentum distribution  
(on-shell partons with  
 $p_t > 2 \text{ GeV}/c$ ) ← PYTHIA 6.2

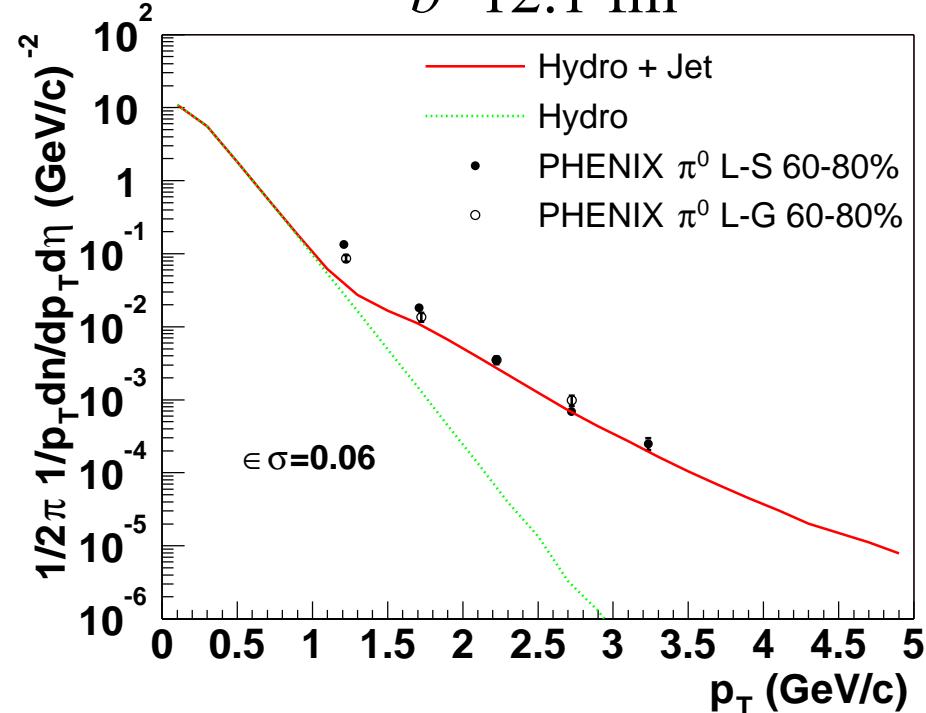
- Assuming partons move along straight paths
- Stop just after coming out from the QGP and mixed phases

# $\pi^0$ Spectra @ High $p_T$

$b=3.35$  fm



$b=12.1$  fm



$$\frac{dE}{dx} = 0.06\rho \Leftrightarrow 0.2 \quad (\text{GeV/fm})$$

$$b=3.35\text{fm} \begin{cases} \Delta E = 550.55 \text{ GeV} \\ E_{\text{hydro}} = 21200 \text{ GeV} \\ \Delta E/E_{\text{hydro}} = 0.0259 \end{cases}$$

# What's New ?

## 1. Full 3D hydro in $\tau$ - $\eta_s$ coordinate

- Rapidity dependence of
    - particle multiplicity
    - radial and elliptic flow
    - HBT radii
- in non-central collisions

## 3. The Hydro + Jet model

- Quantitative estimation of jet quenching
  - Suppression of high  $p_t$  hadrons
  - Saturation of elliptic flow?

## 2. Incorporating early chemical freeze out

- More realistic picture of hydrodynamic behavior
- Particle ratio  $\leftarrow \mu_B \neq 0$

We are now almost ready to explore all hadronic observables in H.I.C. within a hydro-based tool.



# SPARE SLIDES



# Why Hydrodynamics ?

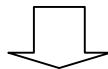
## Theories

### Lattice QCD

- EOS
- Transport coefficient
- Spectral function

### Effective Theories

- Spectral change
- Chiral restoration
- Critical end point



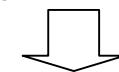
At fixed  $T$  or  $n_B$   
**STATIC!**

large gap!

## Phenomena

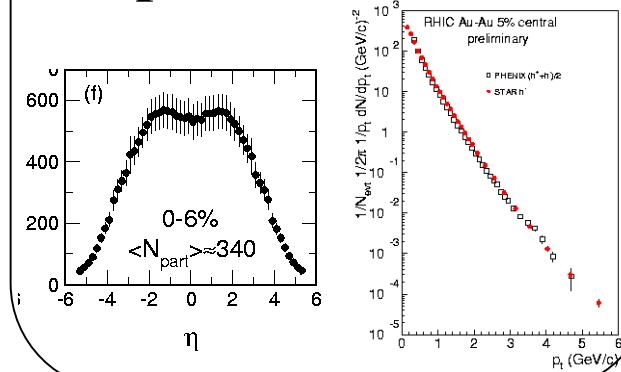
### Heavy-Ion Collisions

- Expansion
- Cooling down
- Flow
- Phase transition



**DYNAMIC!**

### Experimental Data





# HYDRODYNAMICS

**Relativistic Hydrodynamic  
Equation**

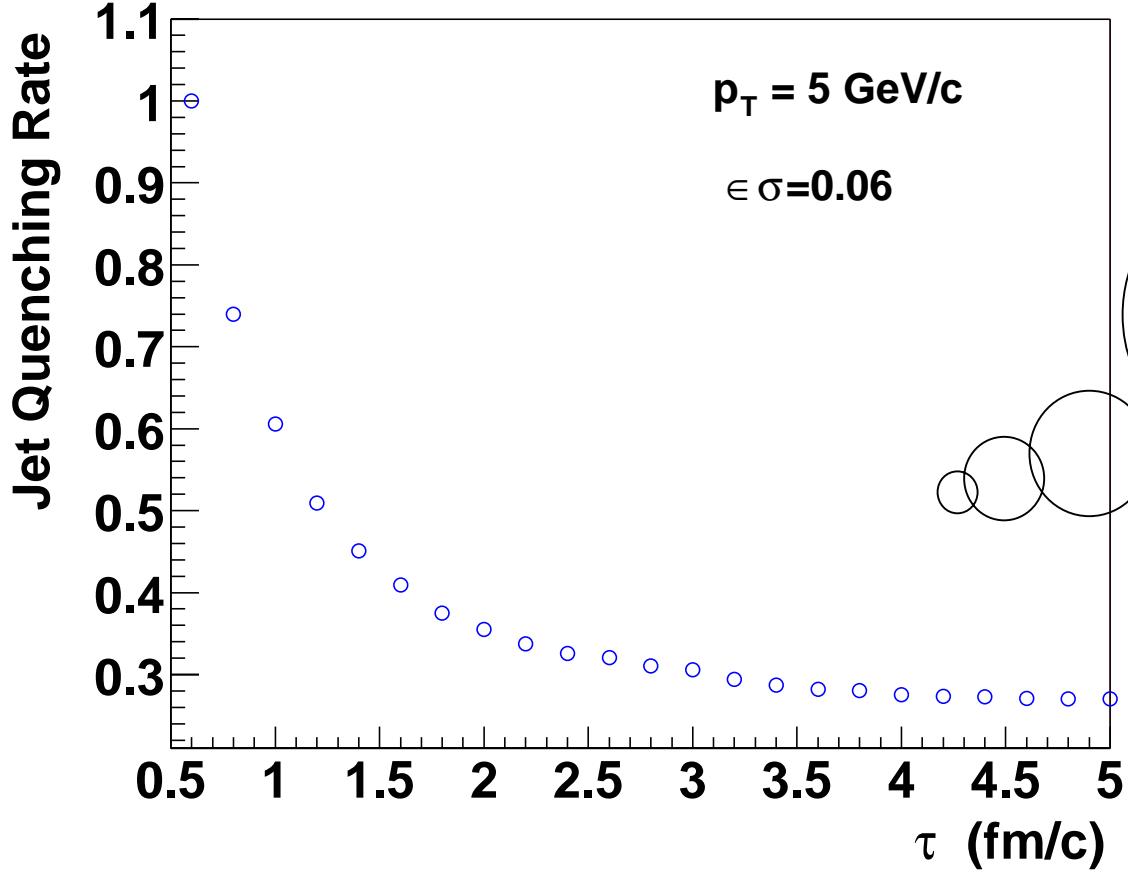
$$\partial_\mu T^{\mu\nu} = 0, \partial_\mu n_B^\mu = 0$$

$$T^{\mu\nu} = (E + P)u^\mu u^\nu - Pg^{\mu\nu}$$

$$n_B^\mu = n_B u^\mu$$

- Space-time evolution of thermodynamic variables
- Phase transition via EOS
- Particle distribution via Cooper-Frye formula

# When Jet Quenching Happens?

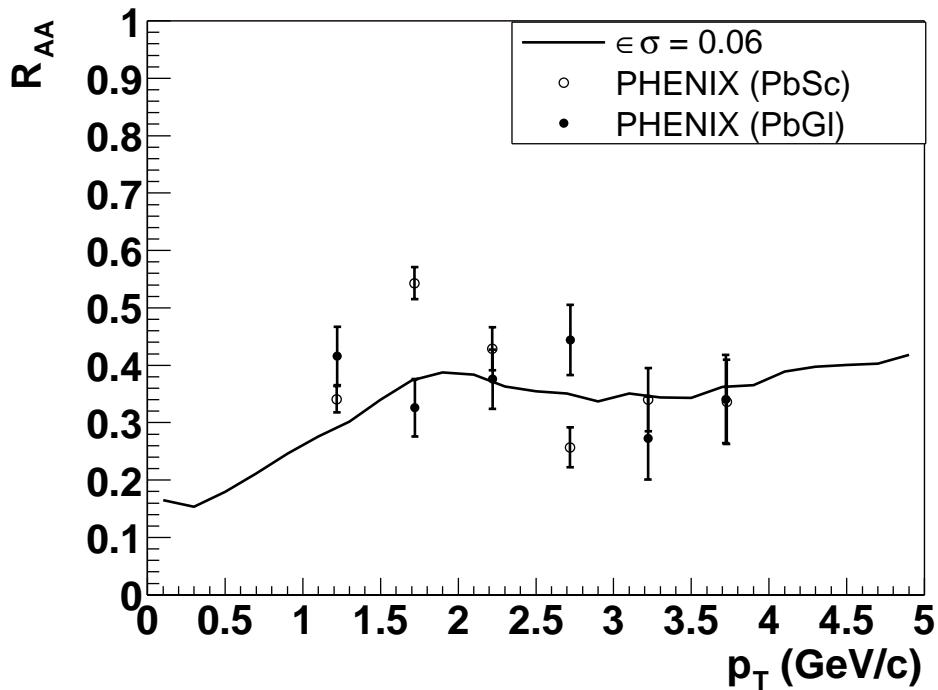


Suppression of high  $p_T$  hadrons

Information on the early stage of parton phase!

$$N(\tau)/N(\tau_0) \text{ at } p_T=5 \text{ GeV}/c, b=3.35 \text{ fm}, \epsilon\sigma=0.06 \text{ GeV fm}^2$$

# Ratio to Binary Collisions at 130A GeV

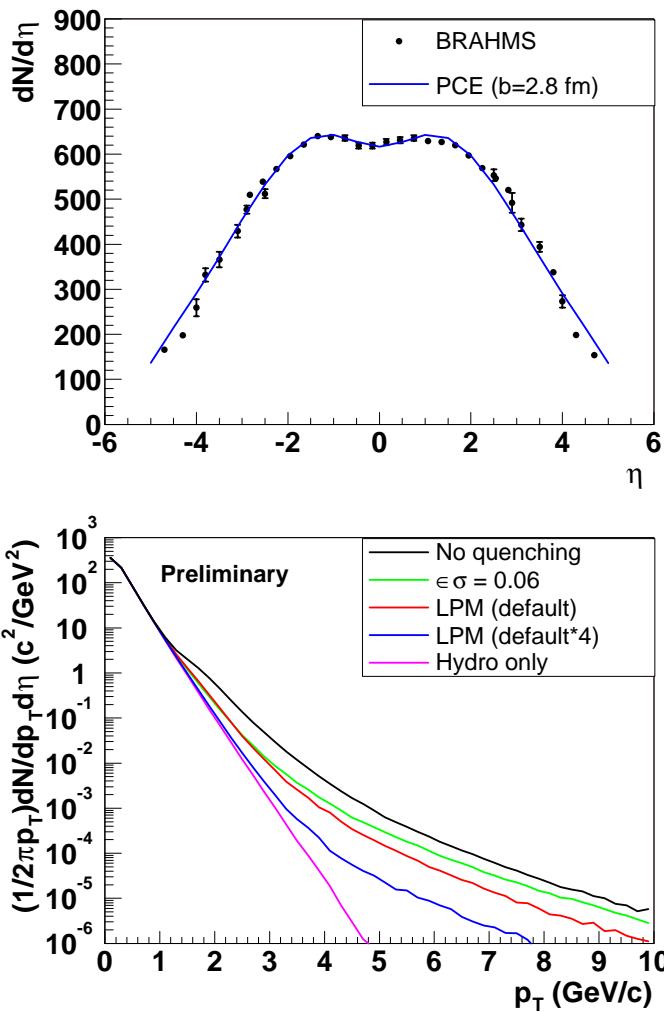


Au+Au 130A GeV collisions  
Impact parameter  $b=3.35\text{fm}$

$$R_{AA}(p_T) = \frac{d^2 N^{A+A} / dp_T d\eta}{\langle N_{\text{binary}} \rangle d^2 N^{N+N} / dp_T d\eta}$$

$R_{AA}$  is increasing with  $p_T$  ?

# $p_T$ Spectra in Au+Au 200A GeV Collisions



**Parton energy loss**

Incoherent:

$$\frac{dE}{dx} = \epsilon \sigma \rho = 0.06 \rho$$

LPM:

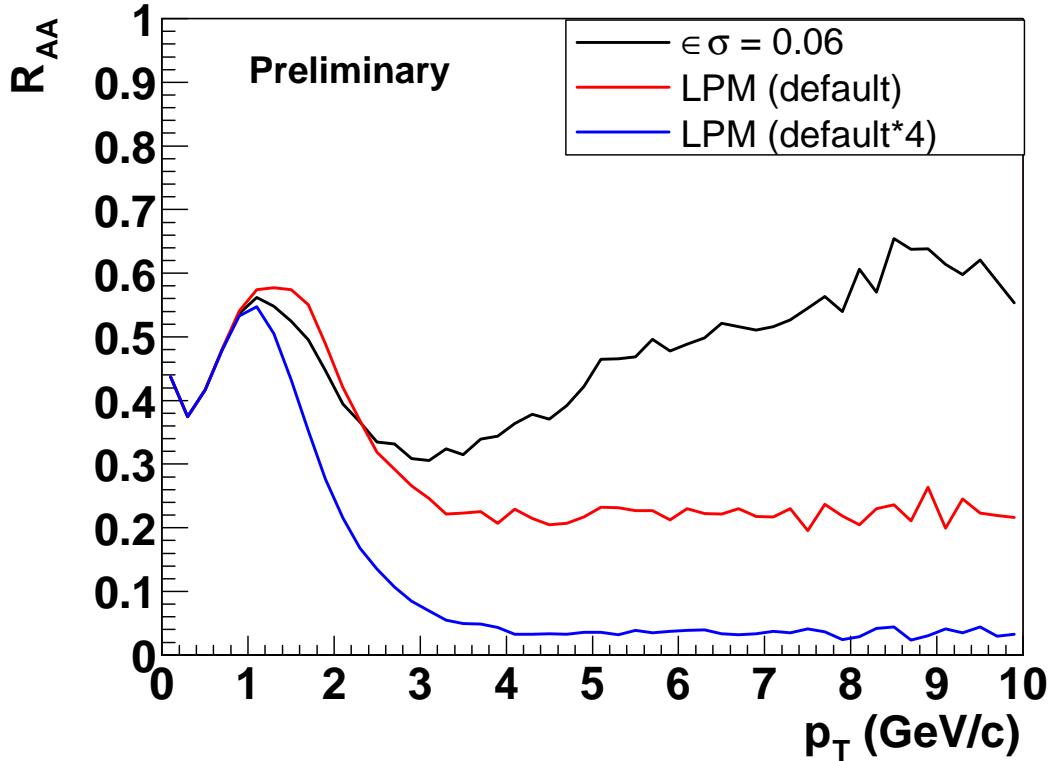
$$\frac{dE}{dx} = a \sqrt{bE} \log\left(1 + \frac{2E}{m^2 L}\right) \rho$$

$$a = 0.08 \text{ fm}^{-1}, b = 0.35 \text{ GeV}$$

$$L \sim 7 \text{ fm}$$

$m$ : screening mass from the Polyakov loop model

# Ratio to Binary Collisions



$$R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_T d\eta}{\langle N_{\text{binary}} \rangle d^2N^{N+N}/dp_T d\eta}$$

Au+Au 200A GeV  
Impact parameter  $b=2.0\text{fm}$

Parton energy loss:

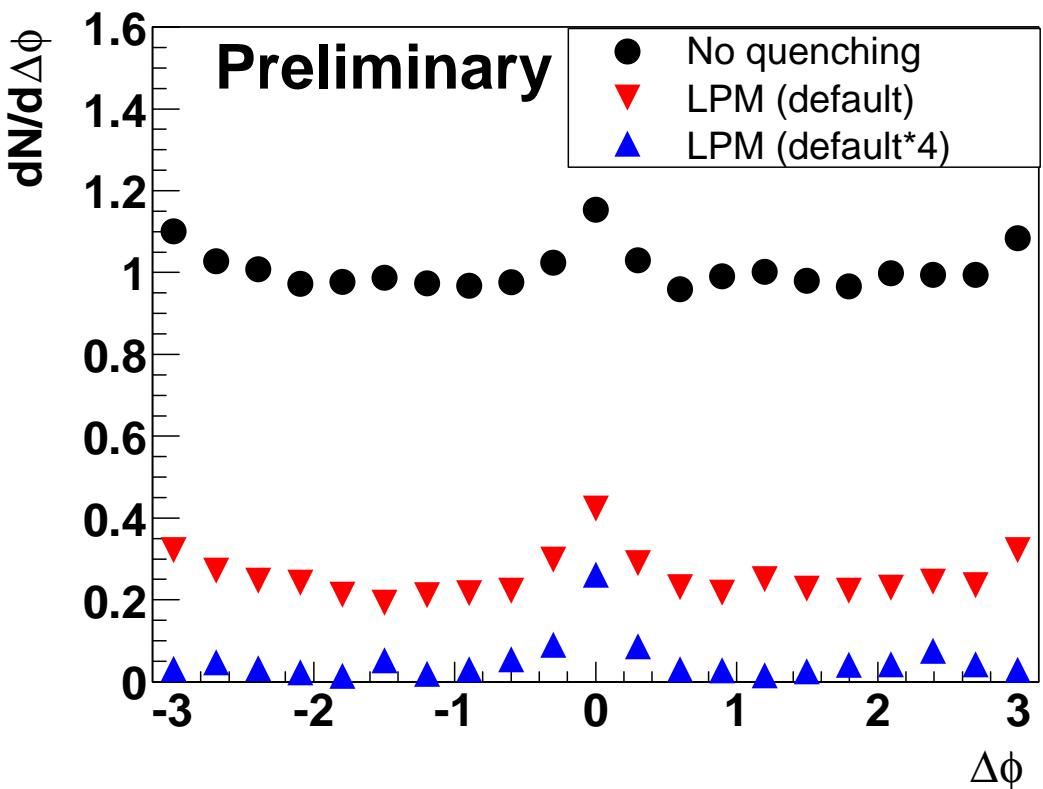
$$\frac{dE}{dx} = a\sqrt{bE} \log\left(1 + \frac{2E}{m^2 L}\right)\rho$$

$$a=0.08\text{fm}^{-1}, b=0.35\text{GeV}$$

$$L \sim 7\text{fm}$$

$m$ : screening mass from the Polyakov loop model

# (Disappearance of) Back-to-Back Correlation



Triggered:  $4 < p_T < 6$  GeV/c, associated:  $2 < p_T < p_{T,\text{trig}}$

Au+Au 200A GeV  
Impact parameter  $b=2.0\text{fm}$

Parton energy loss:

$$\frac{dE}{dx} = a\sqrt{bE} \log\left(1 + \frac{2E}{m^2 L}\right) \rho$$

$$a=0.08\text{fm}^{-1}, b=0.35\text{GeV}$$

$$L \sim 7\text{fm}$$

$m$ : screening mass from  
the Polyakov loop model